Short communication

Vineyard weed management practices influence nitrate leaching and nitrous oxide emissions

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ARTICLE INFO

ABSTRACT

Successive years of multiple tillage passes have been linked to reductions in soil carbon (C) and shifts in soil physical properties, which are often linked to changes in soil nitrogen (N) retention. 'Under the vine' cultivation is becoming a more common practice in vineyards as growers seek alternative means of weed control. Therefore, we (1) investigated the effects of cultivation or herbicide on soil N leaching during a 1 year cycle of vineyard management and (2) determined differences in short-term nitrous oxide (N_2O) emissions and N transformations between 'under the vine' treatments during summer fertigation, a period in which we hypothesized that high N_2O emission rates would occur under warm, moist soil conditions. Few differences were found in the chemical and physical characteristics of soil profiles in cultivated and herbicide treatments. In the surface depths, total C and microbial biomass (i.e., total phospholipid fatty acids) were greater in the tilled than herbicide soils. This contrasts with other findings, but suggests that the greater weed biomass in the tilled treatment contributed labile C to soil C pools. Greater soil nitrate was found at depth (1.2 m) in the herbicide than cultivated treatment. Also, the cultivated soil had nearly 50% less nitrous oxide emissions during fertigation than the herbicide soil. We suggest that greater weed presence, soil C and microbial biomass in the tilled treatment contributed to the greater N retention.

Published by Elsevier B.V.

1. Introduction

Given current climate change mitigation policies, global greenhouse gas (GHG) emissions will continue to increase over the next few decades (IPCC, 2007). We lack data on N_2O from vineyard systems worldwide (but see Steenwerth and Belina, 2008), yet they cover more than 5.5 million ha across Europe, Australia, New Zealand, Africa, and the United States (Anon., 2005). Recently, California (USA) entered the arena to mitigate its GHG emissions with the passage of the California Global Warming Solutions Act of 2006 (State Assembly Bill 32), but emissions from agriculture are not yet regulated.

In vineyard systems, inorganic N fertilizer is often delivered through drip irrigation lines (i.e., fertigation) in summer, a period when warm temperatures and relatively high soil water content can enhance N_2O emissions. The GHG N_2O is produced via nitrification and denitrification, two microbial processes affected by soil N availability, temperature, soil organic matter (SOM), and water and oxygen contents (Drury et al., 1991; Schjønning et al., 2003; Dalal et al., 2003). N_2O production is related to soil N availability (Izaurralde et al., 2004), nitrification and/or denitrification rates, the relative proportions of endproducts produced by nitrifying and denitrifying microbes, and effects of gaseous diffusion on consumption and release of N gases from the soil (Firestone and Davidson, 1989). It is also produced by assimilatory nitrate reduction, which is considered to play a minor role. Soil nitrate (NO_3^-) is likewise produced via nitrification and is susceptible to leaching if not immobilized by plants or soil microbes.

Grape growers employ weed management practices in the vine row ('under the vine') that involve cultivation and/or herbicide. Cultivation can lead to subsequent changes in soil characteristics that influence soil nitrogen (N) dynamics and loss (Jackson et al., 2003). In annual cropping systems, loss of soil N can occur through tillage, which elicits short-term bursts of mineralization of organic N substrates and N_2O emissions, potentially leading to long-term reductions in soil N content without N addition (Calderón et al., 2001; Grandy and Robertson, 2006). Repeated tillage reduces soil carbon (C) content by exposing protected organic matter to microbial consumption and oxidation (Reicosky et al., 1997). Soil C content is directly correlated with soil N availability and N_2O emissions, suggesting that reductions in soil C content induced by tillage will directly influence soil N retention (Lee et al., 2009; Kong et al., 2009).

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To address the dearth of information known about effects of 'under the vine' practices on soil characteristics, N_2O emissions and associated N dynamics in vineyards, we assessed impacts of two 'under the vine' management practices, cultivation and herbicide, on NO_3^- leaching and short-term N_2O emissions. We hypothesized that short-term N transformations and leaching would be greater from the cultivated than herbicide treatment due to soil C loss from five successive years of tillage. Our objectives were to assess (1) N leaching during a 1 year cycle of vineyard management and (2) differences in short-term N_2O emissions and N transformations between 'under the vine' treatments during summer fertigation.

2. Materials and methods

2.1. Site description and experimental design

This study was conducted in a vineyard in the Central Coast region of California (Greenfield, Monterey County, CA). It was planted with Chardonnay on Teleki 5C rootstock in an east-west orientation in 1997 ($1.8\,m \times 2.4\,m$ spacing). Two weed control treatments had been established in late 2001 (Smith et al., 2008). Weeds were managed by (1) mechanically cultivating with a Clemens® vineyard cultivators ('under the vine') as needed (four to six times per year) ('Cultivation') or (2) applying pre- and post-emergent herbicide (simazine [$2.45\,kg\,a.i.\,ha^{-1}$] + oxyflourfen [$1.6\,kg\,a.i.\,ha^{-1}$] applied in winter, followed by 2% glyphosate + 25% oxyfluorfen applied as needed in summer) ('Herbicide') using a Weedseeker® (Ntech, Inc., Ukiah, CA). Four adjacent vines ($4.45\,m^2\,vine^{-1}$) within each weed management treatment were selected, and drip emitters were plugged on one side of each vine. This resulted in a factorial design (i.e., 'Cultivation-drip', 'Cultivation-no drip', 'Herbicide-drip', 'Herbicide-no drip'; $n = 4$). Irrigation occurred 23 times, beginning in January 2006 to hydrate the soil profile (38–96 L per vine per event; annual total of 1130 L per vine, Nov. 2005–Nov. 2006).

The climate in Greenfield is Mediterranean, with cool, wet winters and warm, dry summers. Average daily temperatures range from 8 °C in winter to 19 °C in summer; annual rainfall in the winter of 2005–2006 was 21 cm (California Irrigation Management Information System [CIMIS], url: cimis.water.ca.gov) (See Steenwerth and Belina, 2008). The 14-year mean annual precipitation was 32.0 ± 5.1 cm (#113, King City Station, 20 km southeast, http://www.cimis.water.ca.gov). Soil type was the Elder loam series with gravelly substratum (Coarse-loamy, mixed, superactive, thermic Cumulic Haploxeroll; or, Haplic Chernozem) (Cook, 1978).

2.2. Ion exchange resin bags

To assess annual leaching of soil inorganic N, soil pits were excavated to 1.25 m immediately adjacent to the 'under the vine' treatments. Four anionic exchange resin bags (40 g, 10 cm diam.; Lewatit Monoplus M-5000, Sybron Chemicals, Birmingham, NJ) were placed at 1.2 m depth under 'Drip' and 'No Drip' positions, below the majority of the grapevine root zone (Nov. 1, 2005) (Dodd et al., 2000). After removal (Nov. 30, 2006), nitrate (NO_3^--N) and ammonium (NH_4^+-N) on resin were extracted three times with equal volumes of 2 M KCl (200 mL) and measured colorimetrically (Kempers and Kok, 1989; Miranda et al., 2001). Inorganic N extracted from each bag was combined to yield total inorganic N content at each location.

2.3. Soil pits

When pits were re-opened and resin bags removed in Nov. 2006, soil was collected from the soil volume directly above the resin bags. Soil was collected from each treatment at five depths (0–15,

15–30, 30–55, 55–80, and 80–105 cm). This gave a factorial design of $n = 8$ for each weed treatment and $n = 8$ for 'Drip' versus 'No Drip' at each of the five depths. Soil from the pits was measured for gravimetric water content (θ_g) (75 g, 105 °C for 45 h), NO_3^--N, and NH_4^+-N. Inorganic N in each depth by treatment combination was extracted from three subreplicates of soil (7 g wet wt.; 2 M KCl, 5:1 KCl:soil), and measured colorimetrically, as described previously. Bulk density (ρ_s) was calculated from soil dry weight and the known volume of metal cylinders (8 cm diam. × 10 cm depth) inserted at each sample location/depth. Total soluble N was extracted with 0.5 M K_2SO_4 and measured on a Shimadzu TNM-1 unit (Shimadzu Scientific Instruments, Columbia, MD, USA). Dissolved organic N (DON) was calculated by: ([total soluble N] − [total inorganic N], total inorganic N = NO_3^--N + NH_4^+-N). Potential net N mineralization was measured by anaerobic incubation at 40 °C for 7 days (Waring and Bremner, 1964). Dissolved organic C (DOC) was extracted with 0.5 M K_2SO_4 and measured on a Shimadzu TOC-V_{CSH} unit (Shimadzu Scientific Instruments, Columbia, MD, USA). Potential soil respiration was measured by placing soil (40% WFPS) in sealed jars (946 mL), equilibrating at 4 °C for 24 h, warming to 25 °C, aerating with forced air for 1 min, resealing, and then measuring the difference in headspace CO_2-C concentration after 24 h at 25 °C. Headspace CO_2 levels were measured using an infrared CO_2 analyzer (model PIR-2000R; Horiba Instruments, Irvine, CA USA). Soil was measured for: texture, cation exchange capacity (CEC), pH by saturated paste, percent total N and C, Olsen P, and exchangeable potassium (X-K^+), sodium, calcium, and magnesium (url: danranlab.ucdavis.edu).

2.4. N dynamics following fertigation

Fertigation occurred on March 8, 2006 ($8.18\,kg\,N\,ha^{-1}$ and $24.54\,kg\,P\,ha^{-1}$; Deerpoint 7-21-0, Deerpoint, Fresno, CA) and June 19, 2006 ($31.8\,kg\,N\,ha^{-1}$; ammonium nitrate urea solution 32-0-0: 45.2% NH_4NO_3 and 34.8% urea by weight). After fertigation (ca. 2 h), the vineyard was irrigated for 6 h. Post-fertigation sampling dates were: June 19 (day 0) at 12 p.m.; June 20–21 (day 1–2) at 9 a.m., 12 p.m., and 4 p.m. Subsequent samplings occurred within 24 h of irrigation: June 29 (day 11), July 6 (day 18) and July 21 (day 33) at 12 p.m.

N_2O gas samples were collected using a static chamber method (Folorunso and Rolston, 1984). PVC rings (5 cm depth × 20 cm diameter) were permanently installed in the ground 1 month prior to fertigation. Gas samples (13 mL in 12 mL Exetainer vials; Labco Limited, Buckinghamshire, England) were collected every 30 min for 1.5 h and were measured for N_2O (HP 6890, ECD detector; Agilent Technologies, Santa Clara, CA USA). Inorganic N pools, θ_g, and soil temperature (Hobo) were measured from adjacent vines.

2.5. Statistical analysis

Main effects and interactions were determined by analysis of variance using a mixed model (*proc mixed*, covariance model *AR1*; SAS v. 8.2, SAS Institute, Cary, NC, USA). Variables from the resin and soil pit components were analyzed as factorial designs consisting of all possible interaction effect combinations (resin: weed treatment and irrigation; soil pits: weed treatment, irrigation, and depth). Variables from the fertigation component were analyzed using a repeated measures model comprised of all factorial interactions (weed treatment, irrigation, and time; *proc mixed*, covariance model *AR1*; SAS v. 8.2, SAS Institute, Cary, NC, USA). Multiple comparisons were run using the Tukey adjustment for the resin and soil pit data, and the Bonferroni correction (α/n) for the fertigation data ($\alpha = 0.05$). Prior to analysis, all variables were transformed for normality except ρ_s, CEC, X-cations, percent soil N and pH.

Table 1
Means and standard errors ($x \pm se$) of soil characteristics from 0 to 105 cm ($n=8$).

Soil characteristic	0–15 cm	16–30 cm	31–55 cm	56–80 cm	81–105 cm
Sand (%)	59.8 ± 0.4	60.4 ± 0.4	61.3 ± 0.4	60.9 ± 0.5	60.3 ± 0.4
Silt (%)	24.3 ± 0.4	23.9 ± 0.4	24.1 ± 0.5	24.4 ± 0.4	24.6 ± 0.4
Clay (%)	15.8 ± 0.2	15.7 ± 0.3	14.6 ± 0.3	14.7 ± 0.4	15.1 ± 0.2
CEC ($cmol_c\,kg^{-1}$)	15.41 ± 0.25	15.13 ± 0.22	16.15 ± 0.33	17.23 ± 0.44	17.11 ± 0.32
X-K$^+$ ($cmol_c\,kg^{-1}$)	0.44 ± 0.02	0.44 ± 0.01	0.28 ± 0.02	0.21 ± 0.01	0.25 ± 0.01
X-Na$^+$ ($cmol_c\,kg^{-1}$)	0.40 ± 0.02	0.33 ± 0.01	0.46 ± 0.03	0.65 ± 0.03	0.69 ± 0.04
X-Ca^{2+} ($cmol_c\,kg^{-1}$)	9.26 ± 0.16	8.34 ± 0.12	9.33 ± 0.17	10.48 ± 0.13	10.76 ± 0.13
X-Mg^{2+} ($cmol_c\,kg^{-1}$)	3.78 ± 0.04	3.46 ± 0.03	3.66 ± 0.07	4.10 ± 0.11	3.94 ± 0.06
Olsen P ($mg\,kg^{-1}$)	14.16 ± 0.99	12.88 ± 0.96	8.46 ± 1.11	6.03 ± 0.65	8.25 ± 0.75
pH	7.71 ± 0.06	7.68 ± 0.04	7.59 ± 0.04	7.68 ± 0.04	7.62 ± 0.04
Bulk density ($g\,cm^{-3}$)	1.20 ± 0.02	1.44 ± 0.03	1.36 ± 0.03	1.21 ± 0.03	1.16 ± 0.02
Total C ($g\,g^{-1}$)	0.756 ± 0.024	0.560 ± 0.018	0.475 ± 0.011	0.438 ± 0.009	0.448 ± 0.014
Total N ($g\,g^{-1}$)	0.078 ± 0.002	0.063 ± 0.001	0.058 ± 0.003	0.051 ± 0.002	0.054 ± 0.002
DOC ($\mu g\,g^{-1}$)	68.28 ± 6.80	43.16 ± 3.99	34.04 ± 1.75	34.10 ± 2.58	36.10 ± 0.73
DON ($\mu g\,g^{-1}$)	22.43 ± 6.61	8.54 ± 1.47	5.82 ± 0.26	6.22 ± 0.66	8.18 ± 1.74
Potential respiration ($\mu g\,CO_2$-C g^{-1} 24 h^{-1})	14.22 ± 2.05	3.68 ± 0.44	3.36 ± 0.22	3.26 ± 0.21	3.24 ± 0.24

3. Results

3.1. Shifts in soil characteristics

Soil characteristics, such as soil texture, pH, CEC, and exchangeable cations, did not differ by treatment (data not shown). Soil texture did not differ by depth (Table 1). Only X-K and soil P decreased 40–60% with increasing depth. In general, soil C and N decreased with increasing depth ($P < 0.05$; Table 1). Only total C was greater in 'Cultivation' (0.797 ± 0.036 g C g^{-1}) than 'Herbicide' (0.715 ± 0.024 g C g^{-1}) (weed treatment × depth, $P < 0.05$) from 0 to 15 cm ($n = 4$). Total C and N, NO$_3^-$-N, DON, DOC, potential net mineralizable N and respiration decreased 30–90% from the surface to the lowest depths ($P < 0.05$). Thus, surface soils were enriched in resources important for supporting microbial activity or in common products of microbial decomposition (i.e., DOC, DON, NO$_3^-$-N and NH$_4^+$-N). ρ_s also decreased with increasing depth ($P < 0.0001$), but no other differences were noted.

3.2. Fertigation and N retention

After fertigation, θ_g was greater in 'drip' than 'no drip' soils ($P < 0.05$), but did not differ between weed treatments (Table 2; Fig. 1). Within 'drip' soils, θ_g decreased 40% over the first 3 days after cessation of fertigation. Approximately 24 h after completion of subsequent irrigation cycles (i.e., 6/29, 7/6, 7/21), θ_g of 'drip' soils was similar between the weed treatments and did not differ from θ_g found 24 h after the initial fertigation. Soil temperature tended to be similar between 'Herbicide-drip' and 'Cultivation-drip' (22.8 °C min. to 28.6 °C max.) and between 'Herbicide-no drip' and 'Cultivation-no drip' (data not shown).

During the first 3 days post-fertigation in 'drip' soils, increases in NO$_3^-$-N pools tended to correspond to decreases in NH$_4^+$-N pools (Fig. 1). NH$_4^+$-N concentrations between 'Herbicide-drip' and 'Cultivation-drip' did not differ until nearly 50 h after fertigation ($P < 0.05$), when NH$_4^+$-N of 'Herbicide-drip' decreased by 60% from its initial concentration (Fig. 1, 6/21, 4 p.m.). Decreases were not detectible in 'Cultivation-drip' (Table 2). Soil NO$_3^-$-N concentrations increased in both treatments after fertigation, but soil NO$_3^-$-N concentrations in 'Herbicide-drip' were twice as great as in 'Cultivation-drip' 3 days after fertigation (see Fig. 1, 6/21 12 p.m.). The NH$_4^+$-N and NO$_3^-$-N in 'drip' soils of both management treatments were present in negligible amounts by the subsequent irrigation (Fig. 1, 6/21, 12 p.m.).

Soil N$_2$O-N emissions were greater in 'Herbicide-drip' than 'Cultivation-drip' during the first 1.5 days, at which point the rates in 'Herbicide-drip' decreased to similar rates as 'Cultivation-drip' ($P < 0.05$; Table 2, Fig. 1). Total cumulative N$_2$O-N emissions during the initial fertigation cycle were approximately 50% less in 'Cultivation-drip' than 'Herbicide-drip'. After subsequent irrigations, N$_2$O-N emissions were negligible and did not differ among treatments.

After 1 year, resin bags in 'Herbicide' contained 1283.80 ± 0.03 μg NO$_3^-$-N g^{-1} resin while 'Cultivation' contained just 3.45 ± 0.70 μg NO$_3^-$-N g^{-1} resin ($n = 8$; $P < 0.05$; Fig. 1). A difference between 'drip' and 'no-drip' soils was observed only in 'Herbicide': 'drip', 1487.93 ± 0.03 μg NO$_3^-$-N g^{-1} vs. 'no drip', 1079.67 ± 0.025 μg NO$_3^-$-N g^{-1} ($n = 4$; $P < 0.05$). In fall 2006, the surface depth reflected the effect of weed manage-
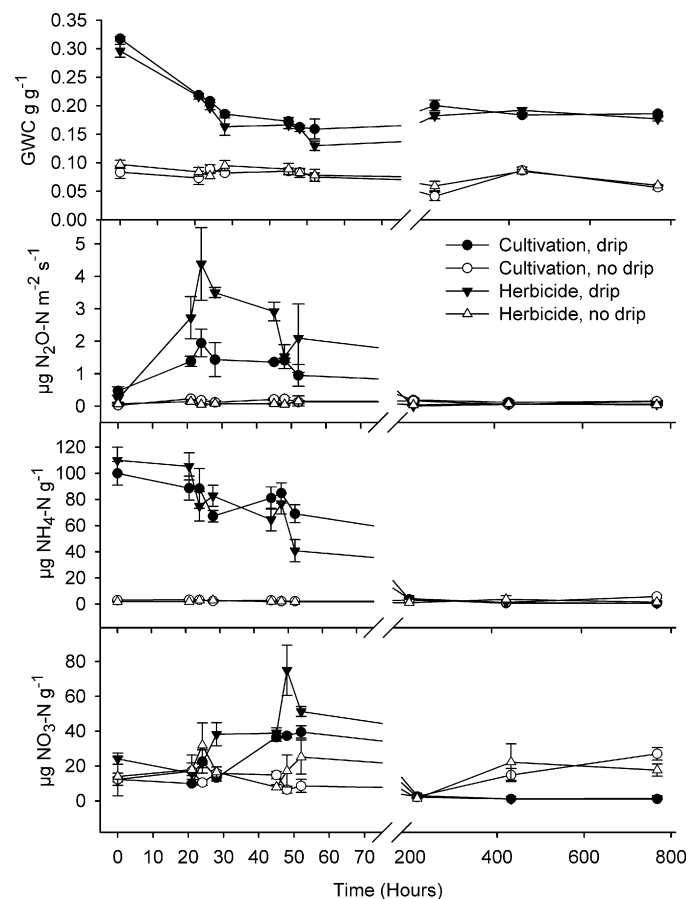

Fig. 1. Means and standard errors of gravimetric water content (GWC), nitrous oxide emissions (N$_2$O-N), soil ammonium (NH$_4^+$-N), and soil nitrate (NO$_3^-$-N) ($n = 4$).

Table 2
P-values for ANOVA of factors measured during fertigation.

	Weed[a]	Drip	Time	Weed × Drip	Weed × Time	Drip × Time	Weed × Drip × Time
θ_g	NS[b]	<0.001	<0.001	<0.001	NS	<0.001	NS
Soil NO_3^--N	<0.05	NS	<0.001	NS	NS	<0.001	NS
Soil NH_4^+-N	<0.01	<0.001	<0.001	<0.05	<0.01	<0.001	<0.01
N_2O	NS	<0.001	<0.001	<0.05	<0.01	<0.001	<0.001

[a] 'Weed' indicates 'Cultivation' or 'Herbicide' treatments. 'Drip' indicates 'drip' or 'no-drip' treatments.

[b] 'NS' indicates that significance at *P* < 0.05 was not achieved.

ment practice on inorganic N pools. Soil NH_4^+-N was greater in 'Cultivation' than 'Herbicide' (0–15 cm: 2.28 ± 0.63 $\mu g\,g^{-1}$, 'Cultivation'; 1.16 ± 0.12 $\mu g\,g^{-1}$, 'Herbicide'; $n = 4$; $P < 0.05$). Soil NO_3^--N in the upper depth of 'Cultivation-drip' soils was greater (5.55 ± 0.13 $\mu g\,NO_3^-$-N g^{-1}, $n = 4$) than 'Herbicide-drip' (1.15 ± 0.74 $\mu g\,NO_3^-$-N g^{-1}, $n = 4$) ($P < 0.05$), and subsurface concentrations of NH_4^+-N and NO_3^--N were similar between weed treatments. Thus, these greater N pools in cultivation than herbicide indicate increased capacity for N availability in 'Cultivation'.

4. Discussion

4.1. Fertigation N dynamics

We hypothesized that short-term N dynamics during fertigation in 'Cultivation' would differ from 'Herbicide' due to reductions in soil C content from successive years of tillage. In fact, our findings provide little support for this hypothesis as 'Cultivation' had slightly greater total C and lower N_2O emission than 'Herbicide'. Using phospholipid fatty acids (PLFA) to measure the viable microbial community and portray labile C, microbial biomass was 3.84 $\mu g\,PLFA\,g^{-1}$ dry soil in 'Herbicide' and 6.15 $\mu g\,PLFA\,g^{-1}$ dry soil in 'Cultivation' ($n = 20$; Steenwerth, unpublished data). We suggest that greater weed presence in 'Cultivation' provided labile soil C substrates that could facilitate greater conversion of N_2O to N_2. Similarly, in a comparison of equivalent additions of organic matter or inorganic N fertilizer in a perennial orchard, N_2O emissions were reduced in the organic treatment, enhancing N_2 emission rates relative to the conventional treatment (Kramer et al., 2006). In addition to grapevine N uptake in both treatments (Christensen et al., 1994), greater weed biomass in 'Cultivation' (60–80% vs. 0–5% in 'Herbicide', personal observation) would also serve as a source for N uptake. Greater weed frequency in 'Cultivation' than 'Herbicide' occurred in the initial 4 years after treatment establishment, contributing to labile C pools (R. Smith, personal communication).

Differences in N_2O emissions between weed treatments also may be partly attributed to physical characteristics. Soil texture, ρ_s, θ_g and temperature did not differ among treatments, indicating that predicted coefficients of gaseous diffusion were similar (Moldrup et al., 1999). Nonetheless, Smith et al. (2008) reported nearly two-fold greater soil compaction from 10 to 18 cm and 18 to 28 cm using a compaction meter in 'Cultivation' than 'Herbicide' (i.e., labeled 'Standard' in their study). Physical disruption of soil structure by tillage likely influenced pore connectivity and tortuosity (Jury et al., 1991), and thus gaseous diffusion. 'Cultivation' also had slightly greater soil C content, indicating potential differences in soil aggregation and tortuosity between weed treatments (Álvaro-Fuentes et al., 2009).

Fertilizer N was highly concentrated in the drip zone relative to a broadcast application as well as the total field rate (i.e., 31 kg ha^{-1}), leading to higher than anticipated NH_4^+-N and NO_3^--N concentrations, and N_2O emissions from the drip zone. We estimate that the wetted surface area was just 0.09 m^2, representing 2% of the total area per vine (4.45 m^2 vine^{-1}) in this vineyard.

4.2. Nitrate leaching

Our findings do not support our original hypothesis that 'Cultivation' would have greater losses of inorganic N due to relatively lower soil C content related to tillage history. Similar nitrate concentrations on the resin between 'drip' and 'no drip' in both weed treatments suggests that inorganic N from 'drip' soils moved laterally after fertigation, or the N found previously in the soil was leached. In a comparison of organic and conventional practices in an apple orchard, an equivalent amount of N fertilizer was broadcast in either mineral or organic form (Kramer et al., 2006). Subsequently, less nitrate was leached in the organic practice, which was attributed in part to sole addition of N via organic matter inputs (Kramer et al., 2006). By extension, this finding alludes to the import of higher soil C content, microbial biomass, and greater weed residues in 'Cultivation' on N retention (Jackson, 2000; Steenwerth and Belina, 2008). Kramer et al. (2006) suggested that the increased performance and efficiency of denitrifiers contributed in part to reduced N leaching. The relatively greater soil C content and microbial biomass, reduced N_2O emissions, and negligible nitrate leaching in 'Cultivation' as compared to 'Herbicide' suggests that this phenomena may have occurred here. Also, the greater annual weed growth in 'Cultivation' than 'Herbicide' likely provided a sink for soil inorganic N, which may have reduced N loss during the year (Jackson, 2000).

The amount of inorganic N that was leached can be expressed as a percentage of total applied fertilizer N. The amount of N present on the resin was estimated with respect to the area associated with an individual vine as determined by vine spacing (4.45 m^2). In this estimation, the amount present on the resin bags was doubled as vines in this vineyard were fertilized by two emitters. Therefore, the estimated annual leaching from 'Herbicide' was approximately 3% of the total N applied. This loss was relatively small as compared to annual cropping systems, such as no-till corn, with reported losses between 11 and 40% of applied fertilizer N (Powers et al., 2000). We suggest that 3% is likely an underestimation as we do not know the exact column size of the soil above the resin bags or the fraction of the wetting front they intercepted.

Our findings suggest that reductions in N loss may be achieved by altering 'under the vine' weed management practices that enhance soil C content and facilitate N retention by vegetation (i.e., weeds), but this hypothesis should be investigated further over multiple years. Facilitating greater internal N cycling is imperative as fossil fuel-derived N fertilizers become less available due to notably finite stocks of fossil fuel. Herbicide and tillage practices influence grapevine N supply and weed pressure, and as such, further evaluation of 'under the vine' weed management practices should include impacts not only on soil N retention but weed establishment, vine N status, and fossil fuel use, and impacts from dust generated by tillage practices that influence air quality (e.g., Baker et al., 2005).

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